WAFER CHARACTERISTICS VIA REFLECTOMETRY

Contractual Origin of the Invention

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Technical Field

The subject matter disclosed herein generally relates to reflectometry methods, devices and systems suitable for use in characterizing wafers.

Background Art

Wafers find a variety of uses in the semiconductor, solar energy and other industries. Wafer quality often depends on variables such as thickness and surface characteristics. Depending on end use, poor quality wafers may have uneven thickness or uneven surface characteristics; whereas, higher quality wafers may have substantially uniform thickness and substantially uniform surface characteristics. In the semiconductor industry, where wafers are used as a substrate, wafer quality can crucially influence mechanical and/or electronic yield of wafer-based semiconductor circuits.

Wafer thickness can affect mechanical, electronic and optical behavior or performance. With respect to mechanical performance, increased thickness can minimize detrimental effects of fabrication or use associated stresses. With respect to electronic and optical performance, wafer thickness is often an important variable. Further, wafer thickness is often defined by distance between an upper wafer surface and a lower

wafer surface. Characteristics of one or both of these surfaces generally affect electronic and optical performance.

Industries that rely on wafer-based technologies typically seek to control wafer thickness through any of a variety of conventional manufacturing and measurement techniques. In the semiconductor industry, wafer thickness may be controlled through various processing techniques that involve wafering (sawing), etching, and polishing, which typically produce flat wafers with substantially parallel surfaces. Thickness measurement of such wafers is fairly well defined and straightforward. For example, conventional measurement techniques include use of a dial gauge (e.g., a manual, mechanical measurement, generally used in the laboratory for a small number of wafers) and use of impedance (e.g., measurement of capacitance or eddy current loss in a radio frequency bridge configuration). Some conventional techniques, such as those that rely on impedance, can be implemented in a non-contact manner. For example, a coil may create an electromagnetic field proximate to a wafer, without actually contacting the wafer, and thereby generate one or more eddy currents in the wafer. Information related to the generated current or currents is then used to determine wafer thickness. Various impedance techniques can be quite rapid, on the order of a few seconds for each wafer, but they require knowledge of wafer properties such as resistivity. Further, impedance techniques are not well suited for determining or mapping variations in wafer thickness.

In general, the solar energy industry imposes certain demands on wafer quality. Such demands often need to be amenable to high throughput. For example, a typical manufacturing facility may process 50,000 wafers per day wherein a reasonable fraction of these wafers must be subject to measurement techniques to provide meaningful quality assurance. Concomitantly, such measurement techniques should be quite rapid. Other demands relate to wafer morphology, noting that wafers used in the solar energy industry are typically not flat. For example, silicon-based ribbons can exhibit surfaces that are substantially

non-parallel with substantial variations in surface morphology. In such instances, an "average" thickness measurement and/or a thickness profile is useful. Yet other demands concerns crystallinity, i.e., the crystalline or multi- (or poly-) crystalline nature of wafers. Conventional impedance techniques can produce inaccuracies for multi- or poly-crystalline wafers because of extraneous impedance associated with grain boundaries and defects. Surface characteristics impose other demands because wafers used in the solar energy industry typically have some substantial degree of surface texture that acts to reduce surface reflectance and maximize optical absorption. Various aspects of surface texture can lead to inaccuracies in determination of thickness and/or surface characteristics. For example, surface roughness can be particularly detrimental for determinations based on optical measurement techniques.

Surface texture includes roughness and waviness, in addition, many surfaces have lay (e.g., directional striations across the surface). Roughness includes the finest (shortest spatial wavelength or spatial periodicity) irregularities of a surface. Roughness generally results from a particular production process or material condition. Waviness includes more widely spaced (longer spatial wavelength or spatial periodicity) deviations of a surface from its nominal shape. Waviness errors are intermediate in wavelength between roughness and form error. Note that the distinction between waviness and form error is not always made in practice, and it is not always clear how to make it. Lay refers to the predominant direction of the surface texture. Ordinarily lay is determined by the particular production process and geometry used. For example, turning, milling, drilling, grinding, and other cutting tool machining processes usually produce a surface that has lay: striations or peaks and valleys in the direction that the tool was drawn across the surface. Other processes produce surfaces with no characteristic direction: sand casting, peening, grit blasting, etc. Sometimes these surfaces are said to have a non-directional, particulate, or protuberant lay.

Clearly, the above demands are difficult to meet. The difficulties are further intensified by a need for minimizing the equipment and the measurement costs. The solar cell industry typically uses wafer weighing as a technique for monitoring wafer thickness while impedance-based techniques are often used to measure thickness of a very small number of total wafers in a single wafer production facility.

The solar energy industry has also identified a need to measure the spatial variations in wafer thickness. It has been observed that certain processes are affected by the local variations in the wafer thickness. For example, a process in solar cell fabrication involves firing a metal pattern to produce a low-resistivity contact. This process consists of screen printing a contact and spike-firing it at a temperature of about 800°C in an infrared furnace. In this type of a furnace, the temperature acquired by a wafer depends on wafer thickness. Thus, a wafer that is thicker than the standard wafer (for which the process is optimized) will rise to a higher temperature. This can lead to the metal punching through a junction which will concomitantly degrade the open circuit photo-voltage (e.g., V_{oc}) and fill factor of the solar cell. On the other hand, a thinner wafer may not be sintered properly, resulting (again) in a low fill factor. Of course, similar behavior may occur within different regions of a wafer if wafer thickness is not uniform.

Thus, within the solar energy industry and other industries, a need exists for methods, devices and/or systems for measurement of and determination of wafer variables (e.g., mechanical properties, mechanical behavior, electrical properties, electrical behavior, optical properties, optical behavior, etc.). In particular, a need exists for methods, devices and/or systems that can yield meaningful results for wafers that may have substantial texture (e.g., roughness, etc.) and/or substantially non-parallel surfaces. Further, a need exists for rapid, accurate, and/or low-cost methods, devices and/or systems. Various exemplary methods, devices and methods disclosed herein address aforementioned needs and/or other needs.

Disclosure of the Invention

Various exemplary methods are directed to determining wafer thickness and/or wafer surface characteristics. An exemplary method includes measuring reflectance of a wafer and comparing the measured reflectance to a calculated reflectance or a reflectance stored in a database. Another exemplary method includes selecting a wavelength and comparing a measured reflectance corresponding to the wavelength with another corresponding wavelength to a measured or a calculated wavelength. Various exemplary methods rely on ranges or bounds for wavelengths and/or reflectances. For example, wavelengths corresponding to moderately absorbing regions are suitable for determining wafer thickness or differences in wafer thickness.

An exemplary method includes positioning a wafer on a reflecting support to extend a reflectance range. Alternatively, an exemplary method includes coating a wafer with a reflective material (e.g., capable of creating an impedance mismatch between the wafer and the material).

An exemplary device capable of performing various exemplary methods has an input for receiving a signal that includes spectral information germane to thickness and/or surface characteristics of a wafer, analysis modules and optionally a database. An exemplary reflectometer system optionally includes such a device.

Various exemplary reflectometer chambers include one or more first radiation sources positioned at a first altitudinal angle and one or more second radiation sources positioned at a second altitudinal angle. Accordingly, the first radiation sources may be more suited to illuminating a wafer having certain thickness and/or surface characteristics while the second radiation sources may be more suited to illuminating a wafer having other thickness and/or surface characteristics. An exemplary method includes selecting one or more radiation sources from a group of radiation sources positioned at various altitudinal angles. For example, higher altitude radiation sources may better illuminate a polished wafer while lower altitude radiation sources may better illuminate a wafer having

substantial surface texture. Further, an exemplary reflectometer chamber includes one or more radiation sources positioned on an azimuthally rotatable section of the chamber. An exemplary method includes rotating a section of a chamber to align one or more radiation sources with the geometry of a wafer (e.g., a major axis, etc.).

An exemplary element includes a first aperture and a second aperture wherein the first aperture can transmit reflected radiation to a fiber and the second aperture can transmit reflected radiation to an imager. The exemplary element is optionally slidably positionable with respect to an aperture of a reflectometer.

Brief Description of the Drawings

Features and advantages of the described implementations can be more readily understood by reference to the following description taken in conjunction with the accompanying drawings.

Fig. 1 is an illustration of an exemplary wafer showing incident radiation, reflected radiation and transmitted radiation.

Fig. 2 is a block diagram of an exemplary device for determining wafer thickness and/or surface characteristics.

Fig. 3 is an exemplary plot of calculated reflectance (%) versus wavelength for two hypothetical wafers having polished surfaces and different thicknesses.

Fig. 4 is an exemplary plot of calculated reflectance (%) versus wavelength for two hypothetical wafers having substantial surface texture and support.

Fig. 5 is an exemplary plot of measured reflectance (%) versus wavelength for two wafers of different thickness positioned on a reflective surface.

Fig. 6 is an exemplary plot of calculated reflectance (%) versus wavelength for two hypothetical wafers having different thickness and on a reflective support that further shows a selected total reflectance and corresponding wavelengths.

Fig. 7 is an exemplary plot of calculated reflectance (%) versus wavelength for two hypothetical wafers having different thickness and on a reflective support that further shows a selected wavelength and corresponding reflectances.

Fig. 8 is an exemplary plot of measured reflectance (au) versus wavelength for a wafer on a reflective support and a wafer on a substantially non-reflective support.

Fig. 9 is a comparison of an exemplary plot of measured reflectance versus wavelength and an exemplary plot of calculated reflectance versus wavelength.

Fig. 10 is an exemplary plot of measured reflectance (au) versus wavelength for a wafer having a polished upper surface and a lower surface with substantial surface texture and another wafer having a polished lower surface and an upper surface with substantial surface texture.

Fig. 11 is an exemplary plot of measured reflectance versus wavelength for two wafers having different thickness and/or surface characteristics.

Fig. 12 is a cross-sectional view diagram of an exemplary system that includes a reflectometer.

Fig. 13 is a perspective view diagram of an exemplary reflectometer chamber.

Fig. 14 is a perspective view diagram of another exemplary reflectometer chamber.

Fig. 15 is a cross-sectional view diagram of the exemplary chamber of Fig. 13.

Fig. 16 is a perspective view diagram of an exemplary element and a component of an exemplary chamber.

Fig. 17 is a cross-sectional view diagram of the exemplary element of Fig. 16.

Fig. 18 is a perspective view diagram of an exemplary element, a positioning mechanism and a component of an exemplary chamber.

Fig. 19 is a cross-sectional view diagram of the element of Fig. 18.

Best Mode for Carrying Out the Invention

The following description includes the best mode presently contemplated for practicing various described implementations. This description is not to be taken in a limiting sense, but rather is made merely for the purpose of describing the general principles of the various implementations. The scope of the described implementations should be ascertained with reference to the issued claims.

Reflectance in an Exemplary Wafer

Various exemplary methods, devices and/or systems described herein rely on a total reflectance spectrum of a wafer. While a rigorous description of radiation at the boundary between two media (e.g., air and a wafer, etc.) or within a medium (e.g., a wafer, etc.) may be made using, for example, the Maxwell Equations, for purposes of brevity, a simplified approach is described with respect to Fig. 1.

Fig. 1 shows an exemplary wafer 100 having an upper surface 110 and a lower surface 120 which are substantially parallel and define a wafer thickness, d. Incident radiation, I_i, (e.g., electromagnetic radiation of a particular wavelength or wavelengths) illuminates the upper surface 110 wherein a portion of the incident radiation is reflected, R_i, and another portion is transmitted, $T_i = I_i - R_i$.

In general, radiation experiences a shift in phase and wavelength when traversing a boundary between dissimilar media. Further, radiation typically loses or transfers energy to a medium according to an absorption coefficient, α, which is a material property of the medium. The process of energy absorption is approximated by the following equation (Equation 1) for a transmitted beam:

$$T(x) = T_i \exp(-\alpha x) \qquad (1),$$

where x is a dimension along the thickness, T_i is an initial transmitted beam (e.g., corresponding to transmitted energy) and T(x) is a diminished transmitted beam (e.g., corresponding to a diminished energy) with respect to a distance x along the thickness. Absorption often depends on wavelength as well, for example, the absorption coefficient, α, which may be approximated by $4\pi kx/\lambda$, where λ is wavelength and k is the imaginary part of the optical constant of a medium and directly related to the absorption of a material (e.g., the extinction coefficient). Hence, shorter wavelength radiation typically absorbs more readily than longer wavelength radiation. Further, radiation having a very short wavelength will typically absorb almost entirely within a "skin depth" region at or near an incident boundary or surface.

According to Equation 1, at the lower surface 120, the transmitted energy has a value of $T(d) = T_i \exp(-\alpha d)$ due to absorption of radiation in the exemplary wafer 100. As for the upper surface 110, a boundary exists between the wafer 100 and another medium at the lower surface 120. Hence, radiation that reaches this boundary (e.g., the lower surface 120) will have a reflected portion, $R_{i+1} = T(d) - T_{i+1}$, and a transmitted portion, $T_{i+1} = T(d) - R_{i+1}$. Similarly, the reflected portion of the radiation, R_{i+1}, may eventually reach the boundary between the wafer 100 and another medium at the upper surface 110, wherein yet another portion R_{i+2} will be reflected and yet another portion T_{i+2} will be transmitted.

The exemplary wafer 100 demonstrates how wafer thickness as well as a wafer upper surface (e.g., the surface 110) and a wafer lower surface (e.g., the surface 120) may affect reflectance. While this example illustrates two internal reflections in an actual wafer, when illuminated by appropriated radiation, a wafer may experience thousands of internal reflections and hence emit thousands of transmitted portions. With respect to wavelength, incident radiation having a longer wavelength will typically result in more internal reflections and more transmitted portions than incident radiation having a shorter wavelength.

Total reflectance depends on reflectance, thickness and absorption according to the following equation (Equation 2):

$$R_T = R\left\{1+\left[\frac{(1-R)^2 \cdot e^{-2\alpha d}}{1-R^2 \cdot e^{-2\alpha d}}\right]\right\} \qquad (2),$$

where $R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}$ and n is the index of refraction.

Total transmittance also depends on reflectance, thickness and absorption according to the following equation (Equation 3):

$$T_T = \frac{(1-R)^2 \cdot e^{-2\alpha d}}{1-R^2 \cdot e^{-2\alpha d}} \quad (3).$$

As mentioned in the Background section, a wafer may have any of a variety of surface characteristics, including texture, roughness, waviness, lay (e.g., directional, accurate, circular, radial, particulate, etc.), form or form error (e.g., typically larger scale errors), flaws (e.g., scratches, gauges, burrs, etc.), profile (e.g., line of intersection of a surface with a sectional plane), and others. Various exemplary methods, devices and/or systems disclosed herein are suitable for use in surface characteristic determinations for wafers.

Exemplary Methods for Wafer Thickness and/or Surface Characteristics

An exemplary method for determining wafer thickness and/or surface characteristics depends on information germane to total reflectance of a wafer. For example, an exemplary method includes receiving a signal that includes information germane to total reflectance of a wafer; comparing the information to information in a database (e.g., spectral information, etc.); and determining thickness and/or surface characteristics of the wafer based on the comparing.

To elaborate further, consider a measured reflectance signal or selected segments of a measured reflectance signal. Such a signal typically includes spectral information such as information germane to

total reflectance of a wafer. For example, consider a signal that includes information about R_i and T_{i+2} as shown in Fig. 1. R_i includes information about the upper surface 110 of the wafer 100 and T_{i+2} includes information about the upper surface 110, the lower surface 120 and thickness of the wafer 100. Of course, the number of T_{i+2} like contributions in a signal (e.g., T_{i+4}, T_{i+6}, T_{i+8}, etc.) will increase as the number of internal reflections in the wafer increases.

Once received, information in the signal may then be compared to information (e.g., spectral information for hypothetical wafers, etc.) in a database. In one example, the information in the database corresponds to calculated reflectance spectra for wafers of different thickness and/or surface characteristics. Three general scenarios may arise from this example wherein: (i) surface characteristics of the wafer are known; (ii) thickness of the wafer is known; and (iii) thickness and surface characteristics of the test wafer are unknown. In the first scenario, the known surface characteristics are used to narrow the comparing and more readily determine thickness of the wafer. In the second scenario, the known thickness of the wafer is used to narrow the comparing and more readily determine surface characteristics of the wafer. In the third scenario, the comparing performs a multivariable analysis to match the spectral information of the wafer with calculated spectral information for hypothetical wafers of various thickness and surface characteristics. The comparing may alternatively, or in addition to, compare to spectral information for actual wafers. Such comparisons may use any of a variety of interpolation techniques. Of course, other scenarios may arise, where some information is known a priori but not enough to forego an analysis to match thickness and/or surface characteristics.

While the aforementioned example uses information in a database, yet other examples may perform calculations to generate information and/or to analyze the information germane to total reflectance. For example, an exemplary method includes receiving a signal that includes information germane to total reflectance of a wafer; performing

calculations to generate information (e.g., spectral information, etc.) and/or to analyze the information germane to total reflectance; and determining thickness and/or surface characteristics of the wafer based on the performing. Where calculations generate spectral information for hypothetical wafers, such information is optionally compared to the information germane to total reflectance.

Various exemplary methods may rely on software to perform calculations or to generate information (e.g., spectral information, etc.), which may be suitable for storage in a database. Commercially available software, such as, but not limited to, PV Optics optical modeling and design software for solar cells and modules (National Renewable Energy Laboratory, Division of U.S. Department of Energy) is suitable for performing such calculations. The PV Optics optical modeling and design software can generate information germane to light trapping of a solar cell or module, including multi-junction devices and any semiconductor material. For example, generated information may indicate how much radiation is absorbed as well as how much of each wavelength of radiation is absorbed.

The PV Optics software can also account for textured surfaces common to most solar cells. The PV Optics software can analyze optical impact for very thin layers such as those associated with anti-reflection coatings or thin-film PV materials and reflective metal backings. In addition, PV Optics software can be used for other semiconductor devices such as optical detectors and certain types of display devices. The PV Optics software can also interface with optical processing instruments such as rapid thermal processing furnaces.

Regarding comparing database information or generated information to information germane to total reflectance, commercially available software for statistical analyses may be used. For example, various commercially available software packages allow for single and multivariable regression analyses. Such analyses are suitable for determining whether information germane to total reflectance of a wafer

matches or fits database information or generated information. Further, such analyses may aid in determining thickness and/or surface characteristics of a wafer based on the comparing. For example, if the signal information for a wafer matches (e.g., within some bounds) certain information stored in a database (e.g., for a hypothetical or actual wafer) then a determination may be made as to the thickness and/or surface characteristics of the wafer.

Exemplary Device Capable of Implementing Methods

Fig. 2 shows a block diagram of an exemplary device 200 for implementing various exemplary methods. The device 200 includes a signal input block 210 for receiving a signal that includes information germane to total reflectance of a wafer. One or more appropriate signals may be received, for example, from a measurement unit (e.g., a reflectometer, etc.), an analysis unit (e.g., a computer, etc.), or a storage unit (e.g., database, disk drive, network, etc.). The device 200 further includes a calculator block 220 for performing various calculations. For example, the calculation block 220 optionally includes a generating block 222 for generating information, a comparing block 224 for comparing information, a determining block 226 for determining one or more characteristics (e.g., thickness, surface characteristics, etc.) of a wafer, and another block 228 that allows for other processes. The calculator block 220 is optionally programmable. Further, an exemplary device may rely on software, hardware or a combination of both to perform calculations and/or other functions. Where appropriate, the exemplary device 200 includes a database 230 for storing information.

Exemplary Methods and Reflectance or Wavelength Bounds

Some of the aforementioned exemplary methods and/or devices do not necessarily rely on associating spectral information with any particular reflectance bounds or wavelength bounds. However, as described herein, determinations for wafer thickness and/or surface characteristics

are facilitated by acquiring, receiving, calculating and/or comparing spectral information within certain reflectance and/or wavelength bounds. Hence, various exemplary methods, devices and/or systems use one or more reflectance and/or wavelength bounds. Such bounds may define one or more regions, for example, in a plot of reflectance versus wavelength for a wafer various regions may exist that correspond to reflectance and/or wavelength bounds.

Polished Wafers

Fig. 3 shows an exemplary plot 300 of reflectance (%) versus wavelength, λ (μm), for two hypothetical wafers of different thickness. Calculated data 310 corresponds to a wafer having thickness of approximately 50 μm while calculated data 320 corresponds to a wafer having thickness of approximately 300 μm. In both instances, the wafers have a polished upper surface and a polished lower surface that are substantially parallel.

The plot 300 has three regions, labeled Region I, Region II and Region III. Region I corresponds to smaller wavelength radiation where high absorption occurs along with a high degree of reflection from the polished upper surface. In Region I, the reflectance diminishes substantially exponentially as a function of increasing wavelength (e.g., over the range from approximately 400 nm to approximately 900 nm). Further, in Region I, the calculated data for the 300 μm wafer 320 and the 50 μm wafer 310 exhibit no substantial differences. Hence, spectral information in Region I may provide little help in making thickness determinations. Again, in this example, the upper surfaces of each of the hypothetical wafers have identical characteristics.

Region II corresponds to moderate wavelengths where moderate absorption occurs. Moderate absorption allows for multiple internal reflections, which are effected by surface characteristics of both the upper surface and the lower surface of the wafers. In Region II, reflectance

generally increases with increasing wavelength (e.g., over the range from approximately 900 nm to approximately 1100 nm) and a substantial difference exists between the calculated reflectance data for the 300 μm wafer 320 and the calculated reflectance data for the 50 μm wafer 310. Further, the reflectance for the 50 μm wafer is generally greater than the reflectance for the 300 μm wafer in Region II. Thus, in Region II reflectance generally decreases as a function of wafer thickness. Again, the absorption coefficient, α (e.g., where $\alpha = 4\pi kx/\lambda$), varies proportionally with respect to thickness and inversely with respect to wavelength. For the data in plot 300, k and λ are identical for both hypothetical wafers; thus, the absorption coefficient and data exhibit dependence of absorption coefficient and reflectance on thickness.

Region III corresponds to longer wavelengths wherein the absorption coefficient is even smaller than for Regions I or II. Hence, incident radiation in Region III absorbs weakly. Concomitantly, reflectance varies little for the two wafer thicknesses (e.g., 50 μm and 300 μm) when compared to Region II. Thus, imposition of reflectance and/or wavelength bounds corresponding to Region II can aid in determinations for wafer thickness.

In one instance, data are acquired only for wavelengths corresponding to a moderately absorbing region. In another instance, data are received only for wavelengths corresponding to a moderately absorbing region. In yet another instance, calculated data are calculated only for wavelengths corresponding to a moderately absorbing region. Another instance compares or analyzes only data for wavelengths corresponding to a moderately absorbing region. Of course, for these aforementioned instances, reflectances corresponding to a moderately absorbing region may be substituted for or used in addition to such wavelengths. Yet further, an exemplary method optionally uses a selected wavelength and/or a selected reflectance that correspond to a moderately absorbing region. These instances and/or associated

exemplary methods may be referred to as using reflectance bounds and/or wavelength bounds.

Textured Wafers

Fig. 4 shows an exemplary plot 400 of reflectance (%) versus wavelength, λ (μm), for two hypothetical wafers of different thickness and having substantial surface texture (e.g., roughness or other characteristics representative of unpolished wafers). Calculated data 410 corresponds to a wafer having thickness of approximately 50 μm while calculated data 420 corresponds to a wafer having thickness of approximately 300 μm. In both instances, the wafers have an upper surface and a lower surface that are substantially parallel and have substantial surface texture.

The plot 400 includes three regions wherein Region II is shown. Calculated data 410, 420 exhibit the trends or dependencies described with respect to the calculated data of the hypothetical polished wafers 310, 320 of Fig. 3. However, the data presented in the plot 400 indicates that substantial surface texture can cause a decrease in total reflectance when compared to similar wafers having polished surfaces.

The plot 400 also includes a selected total reflectance, R_T, that corresponds to Region II, the region of moderate absorbance. The selected total reflectance intersects both reflectance curves 410, 420. The selected total reflectance intersects the thin wafer curve 410 at a wavelength λ_1 and intersects the thicker wafer curve 420 at a wavelength λ_2. In this example, λ_1 is less than λ_2, hence, for a selected total reflectance in a moderately absorbing region, wavelength increases with respect to wafer thickness. Note that the hypothetical wafers having polished surfaces exhibit this behavior as well.

An exemplary method includes selecting a total reflectance in a region where a wafer exhibits moderate absorbance and comparing a wavelength corresponding to the selected total reflectance to another

wavelength. Further, the comparing may aid in determining thickness of the wafer.

Wafers on a Reflecting Support or having a Coated Surface

Fig. 5 shows an exemplary plot 500 of reflectance (%) versus wavelength, λ (μm), for two wafers of different thickness and having substantial surface texture (e.g., roughness or other characteristics representative of unpolished wafers) positioned on a reflecting support. Measured data 510 corresponds to a wafer having thickness of approximately 50 μm while measured data 520 corresponds to a wafer having thickness of approximately 300 μm. In both instances, the wafers have an upper surface and a lower surface that are substantially parallel and have substantial surface texture. Details of exemplary measurement techniques or methods are discussed further below.

In this example, use of a reflecting support extends the range or bounds of total reflectance in Region II. Of course, as an alternative to extend the range or bounds, a wafer's lower surface could be coated with a material that increases reflection at the lower surface (e.g., to create a significant impedance mismatch, difference in refractive indexes, etc.). This approach relies on use of reflectance and can enhance measurement sensitivity.

An exemplary method includes positioning a wafer on a reflecting support to extend total reflectance in a moderately absorbing region, illuminating the wafer with radiation corresponding to the region and measuring reflectance of the wafer. Another exemplary method includes coating a surface of a wafer with a reflecting material to extend total reflectance in a moderately absorbing region, illuminating the wafer with radiation corresponding to the region and measuring reflectance of the wafer. In either of these exemplary methods, measured reflectances are optionally compared to other measured or calculated reflectances. Such a comparison can help in determining thickness of a wafer (e.g., actual or relative thickness).

Fig. 6 shows an exemplary plot 600 of reflectance (%) versus wavelength, λ (μm), for two hypothetical wafers of different thickness and having substantial surface texture (e.g., roughness or other characteristics representative of unpolished wafers) positioned on a reflecting support. Calculated data 610 corresponds to a wafer having thickness of approximately 50 μm while measured data 620 corresponds to a wafer having thickness of approximately 300 μm. In both instances, the wafers have an upper surface and a lower surface that are substantially parallel and have substantial surface texture. Further, the reflecting support has properties of an aluminum reflector suitable for use in a reflectometer.

The calculated data presented in the plot 600 are suitable for use in comparing measured and calculated reflectances, which, in turn, can help in determining thickness of a wafer. For example, the plot 600 shows a selected total reflectance, R_T, and corresponding wavelengths λ_1 and λ_2. In this example, the total reflectance is approximately 0.3%, λ_1 is approximately 1.05 μm and λ_2 is approximately 1.3 μm. Such information may be used in, for example, a comparison with data presented in plot 500 of Fig. 5.

Fig. 7 shows a plot 700 that includes the calculated data of the plot 600. However, in the plot 700, a wavelength, λ_S, is selected to yield a first corresponding reflectance, R_1, for a first wafer and a second corresponding reflectance, R_2, for a second wafer. In general, the wavelength, λ_S, is selected to lie within a moderately absorbing region.

An exemplary method includes selecting a wavelength in a moderately absorbing region, measuring and/or calculating a corresponding reflectance for a wafer (e.g., actual or hypothetical) illuminated by radiation at the wavelength. According to this exemplary method, the reflectance is optionally used for comparing reflectances and/or determining thickness of a wafer.

Another exemplary method includes selecting a wavelength in a moderately absorbing region, illuminating a wafer with radiation and then

interposing a suitable narrow-band filter that allows for transmission of radiation having the selected wavelength from the wafer to a radiation detector. Of course, a band of wavelengths (e.g., wavelengths within some bounds) may be selected wherein the band lies substantially within a moderately absorbing region. In general, signal amplitude (e.g., intensity) of the radiation transmitted through such a filter is inversely related to wafer thickness. Hence, under such circumstances, an increase in detected amplitude (e.g., intensity) corresponds to a decrease in wafer thickness. As described further below, such an exemplary method may aid in imaging wafer thickness.

Exemplary Wafers With and Without Reflecting Support

Fig. 8 shows a plot 800 of measured data for wafers with a reflecting surface 810 and without a reflecting surface 820. The data, plotted as reflectance (au) versus wavelength (nm), exhibits extension of reflectance in a moderately absorbing region through use of a reflecting support (or surface). In this example, the wafer is a commercially available double side textured (DST), crystalline Si wafer (c-Si).

Fig. 9 shows a comparison of plotted data 900 that includes a plot 904 of measured data and a plot 908 of calculated data for wafers with a reflecting surface 910, 910' and without a reflecting surface 920, 920'. The data, plotted as reflectance (au) versus wavelength (nm), exhibits extension of reflectance in a moderately absorbing region through use of a reflecting support (or surface). While differences exist between the measured and calculated data, both sets of data exhibit a significant extension of reflectance in a moderately absorbing region.

An exemplary method includes measuring reflectance of a wafer on a first support and measuring reflectance of the wafer on a second support wherein the supports have different reflecting properties. For example, the first support may have a substantially non-reflecting surface and the second support may have a substantially reflecting surface. Such reflectance data may be subsequently compared (e.g., to measured or

calculated data) or otherwise analyzed to aid in determining wafer thickness and/or surface characteristics. A particular implementation of such an exemplary method includes positioning a wafer on a support having controllable reflecting properties (e.g., liquid crystal, etc.) or on a substantially transparent support (or in a holder) wherein an underlying layer has controllable reflecting properties. Of course, more than two supports, reflecting properties, etc., may be used. For example, a liquid crystalline surface may allow for a range of reflecting properties wherein continuous measurement of reflectance of a wafer occurs as the reflecting properties are varied over the range. A resulting curve of reflectance for the wafer versus reflecting properties (e.g., for one or more wavelengths) can aid in determining wafer thickness and/or surface characteristics. An exemplary controller optionally controls a reflecting support as well as a reflectometer (see, e.g., reflectometers described below, etc.) and/or a processing device (e.g., the device 200, etc.).

Exemplary Wafers having Various Surface Characteristics

Fig. 10 shows a plot 1000 of measured reflectance data for a first wafer 1010 having a polished upper surface and a lower surface with substantial texture and measured reflectance data for a second wafer 1020 having an upper surface with substantial texture and a polished lower surface. In this example, the wafers were commercially available multicrystalline Si wafers (mc-Si) with substantially equal thickness. Data in the plot 1000 indicate that reflectance varies with respect to surface characteristics. Further, variations in reflectance exist over a wide range of wavelengths, including wavelengths typically less than and/or typically greater than those associated with moderate absorption. An exemplary method includes measuring reflectance of a wafer at one or more wavelengths and comparing or otherwise analyzing the measured reflectance to determine one or more surface characteristics of the wafer.

Fig. 11 shows a plot 1100 of measured reflectance data for a first wafer 1110 and measured reflectance data for a second wafer 1120. In

this example, the wafers were commercially available mc-Si wafers (approximately 125 mm by 125 mm) having front texture (FT, e.g., upper side texture) and back polished (BP, e.g., lower side polished), each wafer having about a 50 μm bow and an original wafer thickness of approximately 300 μm. Data in the plot 1100 indicate that the first wafer has a thickness less than that of the second wafer, in particular, the first wafer is approximately 20 μm thinner than the second wafer. In this example, one of the wafers was processed using a polishing technique to decrease its thickness by approximately 20 μm. An exemplary method includes determining wafer thickness or a difference in wafer thickness to a resolution equal to or greater than approximately 20 μm.

Various exemplary methods can use measured data that inherently average a wafer or thickness of a wafer. For example, an exemplary method may illuminate an entire wafer and then measure or detect radiation reflected or emitted from the entire wafer. In this example, the measured or detected radiation represents an average and where such a measured or detected value is used to determine thickness, the thickness represents an average thickness of the wafer. The solar energy industry uses any of a variety of different types of wafers, including ribbon wafers. In general, ribbons wafer do not have substantially parallel upper and lower surfaces (e.g., they may be considered non-planar) but rather have a taper that tapers away from the middle of the ribbon wafer. Average thickness is typically a suitable measure for such ribbon wafers and can aid in crystal growth processes or processing.

Mapping or Imaging Wafers

Various exemplary methods described herein are suitable for creating spatial maps or images of wafer thickness. For example, where a narrow-band filter is interposed between a wafer and a CCD array (e.g., a matrix of individual sensing elements) placed at or near the focal plane of an optical imaging setup for the wafer, the two dimensional optical image

will vary with respect to local wafer thickness (e.g., wherein each element senses a radiation intensity that corresponds to an image pixel). Thus, such an image may be considered a quasi-three dimensional wafer image. As mentioned, intensity typically varies inversely to thickness; thus, in such an instance, low local intensity corresponds to a greater thickness and a high local intensity corresponds to a lesser thickness. Again, such a relationship between reflectance and thickness can exist in a moderately absorbing region.

Of course, an exemplary device (e.g., the device 200, etc.) may aid in relating thickness and radiation intensity. While CCD arrays are commonly used as image sensors, other image sensors may also be suitable, including, but not limited to, radiation sensitive film.

Exemplary Reflectometers

Various exemplary methods described herein optionally use a reflectometer (e.g., a reciprocal reflectometer such as a Sopori reflectometer, a PV reflectometer or a GT reflectometer, etc.) to measure or acquire spectral information germane to thickness and/or surface characteristics of a wafer. In general, a reciprocal reflectometer can measure a reflectance spectrum of a wafer in less than approximately 100 ms. Associated reflectometer equipment (e.g., computer, controller, etc.) can deconvolve an acquired reflectance spectrum to separate parameters that relate to various characteristics of a wafer.

Fig. 12 shows a cross-sectional view of an exemplary reflectometer system 1200. Various features of such a system were disclosed in U.S. Patent No. 6,275,295, to Sopori, issued August 14, 2001, which is incorporated herein by reference. With respect to the system 1200, the description herein discloses additional and/or alternative features. The reflectometer of the system 1200, as shown in cross-section (e.g., across an azimuthal angle, Θ, in substantially hemispherical coordinates), includes an axial dimension, z, a radial dimension r and an altitudinal dimension Φ (e.g., an altitudinal angle). The system 1200 includes a

substantially spherical chamber 1204 centered on a z-axis (e.g., $r = 0$) and operatively coupled at a lower end (e.g., at approximately the horizon) to a radiation baffle 1208. In general, a wafer is positioned substantially on the horizon (e.g., $z = 0$) and substantially centered (e.g., center of wafer at approximately $r = 0$). The chamber 1204 includes a plurality of radiation sources 1212, 1212', 1212" arranged at an altitudinal angle (e.g., Φ approximately 60^o) at a distance (e.g., $z = z(RS_2)$) along the z-axis. This particular example includes four radiation sources (referred to collectively as RS_2) wherein the fourth (i.e., a fore source) is not shown.

The system 1200 includes additional radiation sources 1214, 1214' (referred to collectively as RS_1) arranged at a lesser altitudinal angle (e.g., Φ approximately 10^o) and at a lower distance along the z-axis (e.g., $z = z(RS_1)$). These additional radiation sources 1214, 1214' further optionally have associated optical elements 1215, 1215' (e.g., lenses, etc.) to direct radiation at one or more reflective surfaces 1216, 1216' (e.g., mirrors, prisms, etc.), which are located at a relatively large altitudinal angle (e.g., Φ approximately 80^o, etc.) and at a relatively high distance along the z-axis (e.g, $z = z(M)$). In this exemplary system 1200, the radiation sources 1214, 1214' (RS_1) rely on the optical elements 1215, 1215' to direct radiation from the sources to the one or more reflective surfaces 1216, 1216'. In turn, the one or more reflective surfaces 1216, 1216' direct radiation to a wafer 1218, which is positioned at or near the base of the chamber 1204 (e.g., $z = z(W)$ and centered at approximately $r = 0$).

The system 1200 essentially functions by illuminating the wafer 1218 using any or all of the radiation sources (e.g., RS_1, RS_2). In this example, the wafer 1218 lies on a support or platform 1222 attached to an end of a post 1226 positioned within the baffle 1208. Once illuminated, the wafer 1218 reflects radiation toward an opposing end of the chamber 1204 (e.g., substantially normal to an upper surface of the wafer 1218). The opposing end of the chamber 1204 optionally includes an optical element 1230 (e.g., a lens, etc.), set in an upper aperture 1232, that directs the reflected radiation to a collector 1234 (e.g., an optical fiber, a

light pipe, etc.). The optical element 1230 may be adjustable and part of an optical system for measurement (e.g., directing radiation to a detector, etc.) and/or imaging (e.g., having an associated focal length, etc.). The collector 1234 provides a path to a detector or analyzer 1238 for detecting or analyzing the reflected radiation. According to the description herein, the detector or analyzer 1238 optionally includes features or components of the exemplary device 200 of Fig. 2. The exemplary system 1200 may measure reflectance of a wafer as a function of wavelength.

The exemplary system 1200 also includes yet another optical element 1242 (e.g., a semi-transparent mirror, a lens, a prism, etc.) that can direct reflected radiation to another unit 1246 (e.g., an imaging unit, a camera, etc.). The optical element 1242 optionally allows for radiation to reach the collector 1234 and to reach the unit 1246 (e.g., a prism or semi-transparent mirror). Alternatively, a mechanism exists to select either the collector 1234 or the unit 1246 (e.g., a mechanism capable of activating or positioning the optical element 1242). An exemplary element and an associated exemplary mechanism for directing radiation are described further below.

In general, the chamber 1204 has a highly absorbing inner surface that reduces radiation scatter within the chamber 1204, which, in turn, can enhance signal to noise ratio of radiation reflected (e.g., externally or internally) in a direction substantially normal to the wafer 1218 (e.g., along the z-axis). The exemplary system 1200 may achieve a signal to noise ratio of approximately 200.

Wafer Illumination and Surface Characteristics

As already mentioned and exhibited in the plot 1000 of Fig. 10, surface characteristics of a wafer affect reflectance. In general, wafers having substantial surface texture (e.g., roughness, etc.) reflect radiation in a more diffuse manner than wafers having one or more substantially polished surfaces. The exemplary system 1200 can measure reflectance for wafers having substantial surface texture. In particular, the exemplary

system 1200 can perform such measurements using radiation sources positioned at altitudinal angles (e.g., Φ) that are substantially less than 90° (e.g., positioned well off the z-axis or zenith and not substantially normal to a wafer). Such radiation sources (e.g., RS_2) direct radiation in a manner that can illuminate a variety of surface features (e.g., consider a wafer having a jagged profile).

The exemplary system 1200 can also use such radiation sources (e.g., RS_2) to measure reflectance for a wafer having less surface texture, for example, wafers having one or more polished surfaces, particularly an upper polished surface and/or wherein the upper surface is substantially normal to the rz-plane (e.g., substantially parallel to the rΘ-plane). However, reflectance measurements for such wafers may be enhanced through use of radiation that illuminates a wafer from a direction substantially normal to the wafer. The radiation sources RS_1 of the system 1200 can allow for such illumination. Again, the radiation sources 1214, 1214' (RS_1) have associated optical elements 1215, 1215' and reflecting surfaces 1216, 1216' that can direct radiation normal to a wafer.

Fig. 13 shows another exemplary chamber 1300 having another exemplary arrangement of radiation sources. The exemplary chamber 1300 includes an upper section 1304 that has a plurality of radiation sources 1308, 1308', 1308", 1308'" positioned thereon, referred to herein as RS_3 (e.g., being positioned the furthest distance from a wafer along the z-axis: $z(RS_3) > z(RS_2) > z(RS_1)$). The plurality of radiation sources RS_3 are positioned substantially normal to the rΘ-plane (where Θ is the azimuthal angle), for example, at an altitudinal angle Φ equal to or greater than approximately 70°. These radiation sources are suitable for illuminating a wafer with radiation directed substantially normal to the wafer. While the exemplary chamber 1300 has four radiation sources 1308, 1308', 1308", 1308'", a lesser or greater number are optionally used. For example, an exemplary chamber optionally includes a single ring-shaped source positioned at or near an upper aperture 1332, two

sources positioned at altitudinal angles (e.g., Φ) equal to or greater than approximately 70°, or 8 sources positioned at altitudinal angles (e.g., Φ) equal to or greater than approximately 70°, etc.

The exemplary chamber 1300 optionally includes additional radiation sources 1312, 1312', 1312", etc., positioned at lesser altitudinal angles (e.g., Φ), referred to as RS_2. For example, such additional radiation sources may be positioned at altitudinal angles less than approximately 70°. In general, such additional radiation sources may be positioned at altitudinal angles equal to or greater than approximately 30° and less than approximately 70°. These additional sources RS_2 are suitable for illuminating wafers having substantial surface texture (e.g., roughness). Hence, the exemplary chamber 1300, as shown, is suitable for illuminating wafers having a wide variety of surface characteristics. A controller, such as the controller 1238 (Fig. 12), optionally controls radiation sources and may select or adjust illuminating radiation to account for such surface characteristic variations. For example, a controller may provide power to a plurality of radiation sources in a manner that allows for essentially rotational illumination (e.g., sequential illumination at an angular frequency, etc.).

Fig. 14 shows yet another exemplary chamber 1400 having an exemplary arrangement of radiation sources. The exemplary chamber 1400 includes an upper rotatable section 1404 (e.g., rotatable in the azimuthal angle, Θ) that has a plurality of radiation sources 1408, 1408', 1408", 1408'" positioned thereon, referred to herein as RS_3 sources. Hence, rotation of the section 1404 may allow for improved illumination of a wafer having particular geometry. The plurality of radiation sources RS_3 are positioned substantially normal to the rΘ-plane, where Θ is the azimuthal angle (e.g., at an altitudinal angle Φ equal to or greater than approximately 70°). These radiation sources are suitable for illuminating a wafer with radiation directed substantially normal to the wafer. While the exemplary chamber 1400 has four radiation sources 1408, 1408',

1408", 1408"', a lesser or greater number are optionally used. For example, an exemplary chamber optionally includes a single ring-shaped source positioned at or near an upper aperture 1432, two sources positioned at altitudinal angles (e.g., Φ) equal to or greater than approximately 70°, or 8 sources positioned at altitudinal angles (e.g., Φ) equal to or greater than approximately 70°, etc.

The exemplary chamber 1400 optionally includes an additional rotatable section 1410 having additional radiation sources 1412, 1412', 1412", etc., positioned at lesser altitudinal angles (e.g., Φ), referred to as RS_2 sources. Hence, rotation of the section 1410 may allow for improved illumination of a wafer having particular geometry. These additional sources RS_2 are suitable for illuminating wafers having substantial surface texture (e.g., roughness). Hence, the exemplary chamber 1400, as shown, is suitable for illuminating wafers having a wide variety of surface characteristics. A controller, such as the controller 1238 (Fig.12), optionally controls radiation sources and may select or adjust illuminating radiation to account for such surface characteristic variations.

Fig. 15 shows a cross-sectional view of the exemplary chamber 1300 of Fig. 13. This particular cross-section shows the section 1304, two of the radiation sources 1308, 1308", an upper aperture 1332 (e.g., defined by the section 1304) and a wafer 1318. The radiation sources 1308, 1308" are positioned at a distance $z = z(RS_3)$ and at an altitudinal angle $\Phi = \Phi\ (RS_3)$. Again, radiation from the sources 1308, 1308" can illuminate the wafer 1318 from a direction substantially normal to the wafer. Radiation reflected from the wafer 1318 is at least in part directed substantially normal to the wafer (e.g., along the z-axis) and through the upper aperture 1332 of the chamber 1300. The exemplary chamber 1300 is optionally suitable for use in measuring reflectance of wafers having little surface texture (e.g., one or more polished surfaces). In general, the term "polished" refers to a surface characteristic that may be achieved via any of a variety of processing techniques (e.g., including, but not limited to, polishing).

An exemplary method includes illuminating a wafer with radiation from one or more radiation sources positioned at a first altitudinal angle and then illuminating the wafer with radiation from one or more radiation sources positioned at a second altitudinal angle. Such an exemplary method can help in determining thickness and/or surface characteristics of a wafer.

Another exemplary method includes illuminating a wafer having substantial surface texture using one or more radiation sources positioned at a first altitudinal angle and illuminating another wafer having lesser surface texture (e.g., more polished, etc.) using one or more radiation sources positioned at a second altitudinal angle wherein the second altitudinal angle is greater than the first altitudinal angle.

Yet another exemplary method includes measuring reflectance of a wafer and then selecting one or more radiation sources from a group of radiation sources positioned at a plurality of altitudinal angle. Such an exemplary method may help to achieve a more accurate measurement of wafer thickness and/or surface characteristics.

Another exemplary method rotates a section of a chamber to position radiation sources with respect to geometry of a wafer. For example, a rectangular wafer may have a dominant axis (e.g., along a particular azimuthal angle Θ as defined above). In this example, rotation of a section may allow for positioning one or more radiation sources with respect to the dominant axis of the wafer.

Exemplary Element for Directing Reflected Radiation

Fig. 16 shows an exemplary system 1600 having an exemplary element 1650 for directing reflected radiation. For ease of description, the element 1650 is shown with respect to a section 1604 suitable for use as a part of a reflectometry chamber. Of course, the element 1650 is suitable for use with any of a variety of reflectometry chambers (e.g., chamber 1204, chamber 1300, chamber 1400, etc.).

The element 1650 has predominantly rectangular cross-sections which define a plurality of cylindrical apertures including a fore aperture 1654 and an aft aperture 1658. The element 1650 is positionable with respect to the upper aperture 1632 of the section 1604. In particular, the element 1650 is positionable to allow for substantial alignment between the upper aperture 1632 and the fore or aft apertures 1654, 1658. Any of a variety of positioning means may allow for positioning of the element 1650 in such a manner. For example, a sliding mechanism may allow the element 1650 to slide forward and backward thereby allowing for alignment of fore or aft apertures 1654, 1658 and the upper aperture 1632.

An exemplary element includes a first cylindrical aperture to receive a fiber capable of coupling radiation to a detector or analyzer and a second cylindrical aperture to transmit radiation to an imager (e.g., a camera).

Fig. 17 shows a cross-sectional view of the exemplary system 1600 of Fig. 16 and a wafer 1618 positioned in a chamber that has an optical element 1630 set in the upper aperture 1632. In this example, the fore aperture 1654 has a length greater than that of the aft aperture 1658. This arrangement allows for positioning a fiber close to the optical element 1630, which can increase coupling of radiation from the chamber to the fiber.

Fig. 18 shows an exemplary system 1800 having an element 1850 for directing reflected radiation. For ease of description, the element 1850 is shown with respect to a section 1804 suitable for use as a part of a reflectometry chamber. Of course, the element 1850 is suitable for use with any of a variety of reflectometry chambers (e.g., chamber 1204, chamber 1300, chamber 1400, etc.).

The element 1850 has predominantly rectangular cross-sections which define a plurality of cylindrical apertures including a fore aperture 1854 and an aft aperture 1858. The element 1850 is positionable with respect to the upper aperture 1832 of the section 1804. In particular, the

element 1850 is positionable to allow for substantial alignment between the upper aperture 1832 and the fore or aft apertures 1854, 1858. Any of a variety of positioning means may allow for positioning of the element 1850 in such a manner. In the exemplary system 1800, a pair of arms 1860, 1860' extend from the section 1804 to respective sides of the element 1850. In this example, the arms 1860, 1860' allow the element 1850 to slide back and forth with respect to the section 1804 and hence allow for alignment of the fore or aft apertures 1854, 1858 and the upper aperture 1832.

Fig. 19 shows a cross-sectional view of the exemplary system 1800 along with a wafer 1818 positioned in a chamber. In the exemplary system 1800, the arms 1860, 1860' extend from the chamber section 1804 to respective sides of the element 1850. In this example, the arms 1860, 1860' allow the element 1850 to slide back and forth with respect to the section 1804 and hence allow for alignment of the fore or aft apertures 1854, 1858 and the upper aperture 1832. More specifically, in this example, the element 1850 has two rails 1864, 1864' and each arm 1860, 1860' has a groove 1868, 1868' capable of slidably receiving a respective rail 1864, 1864'. Accordingly, the element 1850 is positionable with respect to the upper aperture 1832 of a chamber or section (e.g., section 1804) thereof. Of course, a locking mechanism (e.g., screw, clamp, etc.) or a fine adjustment mechanism (e.g., micrometer type mechanism, etc.) may accompany such an exemplary system.